Prediction of Maximum Liquid-phase Penetration in Diesel Spray: A review

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Key Words: maximum liquid-phase penetration, empirical correlation, multi-dimensional model, diesel spray

Abstract

The correlations for the prediction of maximum liquid-phase penetration in diesel spray are reviewed in this study. The existing models developed for the prediction of maximum liquid-phase penetration can be categorized as the zero-dimensional (empirical) model, the multi-dimensional model and the other model. The existing zero-dimensional model can be classified into four groups and the existing multidimensional models can be classified into three groups. The other model includes holistic hydraulic and spray model. The maximum liquid-phase penetration is mainly affected by nozzle diameter, fuel volatility, injection pressure, ambient gas pressure, ambient gas density and fuel temperature. In the case of empirical correlations incorporated with spray angle, the predicted results will be different according to the selection of correlation for spray angle. The research for the effect of boiling point temperatures on maximum liquid-phase penetration is required. In the case of multidimensional model, there exist problems of the grid and spray sub-models dependency effects.

Nomenclature

C_a : area contraction coefficient
d_0 : nozzle diameter
ΔP : pressure drop across nozzle
L : maximum liquid-phase penetration
S : spray penetration
t : time after start of injection
ρ_f : density of fuel
ρ_a : density of ambient gas
θ : spray angle

1. Introduction

One of main concerns in direct injection diesel engine research is the fuel-air mixture process which is strongly influenced by the spray characteristics of fuel. Among the various spray characteristics, spray penetration is one of significant parameters in terms of fuel-air mixture process and in turn emission control. The spray penetration in diesel engine conditions is the penetration of the mixture of vapor and liquid. For non-evaporating sprays, the vapor part and the liquid part of penetrations are equal. For evaporating sprays, however, the liquid part of the penetration is limited by the lifetime of the droplet. Many studies on the measurement of liquid phase penetration in the evaporating diesel fuel jets have been conducted from around twenty years ago by virtue of the development of planar laser-based diagnostics(1). Initially the liquid part of the penetration is called as liquid core length by Browne et al.(2) Liquid phase penetration by Kamimoto et al.(3), liquid core penetration length by Gulder(4), liquid-phase fuel penetration by Siebers(5) and penetration length of droplets by Wan and Peters(6), liquid spray penetration by Desantes et al.(7), and liquid phase spray penetration by Desantes et al.(8) are also using as synonym for the expression of the liquid part of diesel spray penetration. In this study, vapor-phase penetration

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and liquid-phase penetration will be used for the expression of diesel spray penetration.

As the overall spray continued to penetrate in an evaporating diesel spray, the tip of the liquid-phase fuel region stopped penetrating and remained at nearly a constant axial position. This is called as the maximum axial penetration distance of liquid-phase fuel referred to as the liquid length by Siebers(5). Maximum liquid-phase penetration(9), maximum penetration distance of liquid-phase fuel(10), liquid-phase length(11) and liquid length penetration(12), maximum length of the intact liquid core or break-up length(4), maximum liquid penetration, and spray liquid penetration length are also using as synonym. In this study, maximum liquid-phase penetration is selected and will be used.

Recently, the extensive review on the correlation for the prediction of non-evaporating diesel spray conditions, was reported by the author(13). There exist a few works on the development of correlation for the prediction of liquid-phase penetration in evaporating diesel spray conditions. Main concern was the prediction of maximum liquid-phase penetration in evaporating conditions. The maximum extent of liquid-phase penetration into in-cylinder gases is important parameters in CI and GDI engines design. Excessive maximum liquid-phase penetration can lead to wetting of the piston and cylinder walls, resulting in potentially higher emissions.

The purpose of this paper is, therefore, to review and classify the correlations for predicting the maximum liquid-phase penetration in vaporizing diesel engine conditions and to suggest the future works.

2. Prediction of maximum liquid-phase penetration

The existing models developed for the prediction of liquid-phase penetration can be categorized as the zero-dimensional model, the multi-dimensional model, and other model.

2.1 zero-dimensional(empirical) model

The existing zero-dimensional model (empirical model) for the prediction of maximum liquid-phase penetration can be classified as four groups, i.e. the correlations based on liquid jet break-up time, the correlation for single-component fuels, the correlation for arbitrary fuel blends and statistical correlation.

2.1.1. correlations based on liquid jet breakup time

As a most widely cited empirical correlation, the jet breakup model for the prediction of spray tip penetration by Hiroyasu et al.(14) was derived from the liquid jet disintegration theory. In this model, the spray tip penetration is divided into two zones; the initial zone consists of an intact liquid core and the latter zone consists of a mixture of liquid droplets and entrained medium. The followings are the empirical correlations for the intact liquid core penetration, i.e. liquid-phase penetration and intact liquid core break-up time, respectively.

$$S = 0.55\left(\frac{\Delta p}{\rho_f}\right)^{0.5} t \quad 0 < t < t_b \tag{1}$$

$$t_b = 28.65\frac{\rho_f d_o}{\sqrt{\rho_a \Delta p}} \tag{2}$$

When $t=t_b$, spray tip penetration S gives the maximum length of the intact liquid core, L i.e. break-up length or maximum liquid-phase penetration as follows.

$$L = 15.86 d_o\left(\frac{\rho_f}{\rho_a}\right)^{0.5} \tag{3}$$

On the other hand, Yule et al.(15) proposed the following semi-empirical correlations for the prediction of spray tip penetration.

$$S = 3.8\left[\left(\frac{\Delta P}{\rho_a}\right)^{0.5} d_0 t\right]^{0.5} \tanh[(t/t_b)^{0.6}] \tag{4}$$

where

$$t_b = 3.75\times 10^5 (d_0)^{-0.28}(\rho_a)^{0.05}(\Delta p)^{-1.37} \tag{5}$$

When $t=t_b$, correlation for the prediction of the maximum length of the intact liquid core, i.e. maximum liquid-phase penetration can be obtained as follows.

$$L = 2.9\left(\frac{\Delta p}{\rho_a}\right)^{0.25} (d_0 t_b)^{0.5} \tag{6}$$

According to the prediction of the above two correlations, intact liquid core or liquid-phase penetration is believed to extend up to a few hundred nozzle diameter. However, Gulder et al.[16] found that the intermittent and highly transient nature of diesel sprays ensured rapid and complete atomization within no more than twenty nozzle diameter. In the discussion of the structure of dense diesel sprays, Gulder[4], therefore, concluded that there is no relevance of the structural information obtained from continuous sprays to the characteristics of intermittent diesel sprays. For this reason, the above correlations based on measurements made on steady state sprays should be reassessed.

2.1.2. correlations for single-component fuel

The empirical correlation for the prediction of maximum liquid-phase penetration for single-component fuels was developed by Siebers[10] as follows.

$$L = \frac{b}{a}\sqrt{\frac{\rho_f}{\rho_a}}\frac{\sqrt{C_a}d_0}{\tan(\theta/2)}\sqrt{\left(\frac{2}{B(T_a,P_a,T_f)}+1\right)^2-1} \quad (7)$$

where $B(T_a,P_a,T_f) = \dfrac{h_a(T_a,P_a)-h_a(T_s,P_a-P_s)}{h_f(T)-h_f(T_f,P_a)}$

where h_f and h_a are specific enthalpies of the fuel and ambient gas, respectively. T_s, T_f and T_a are the saturation, injector tip and ambient gas temperatures, respectively. P_s and P_a are partial pressure of the vapor fuel and ambient gas pressure, respectively. The constant a in the above equation has a value of 0.66. A value recommended for the constant b in the above equation is 0.41.

It should be noted that the spray spreading angle was introduced in the development of correlation of maximum liquid-phase penetration. The spreading angle was determined from the following expression.

$$\tan(\theta/2) = A_x/(x_2^2-x_1^2) \quad (8)$$

The term x_1 and x_2 in Eq. (8) are the axial distance of 2.5 mm from the injector tip and a distance 20% longer than the liquid length, respectively. The area A_x is the area in the image between the distance x_1 and x_2 with an intensity below the threshold.

On the other hand, an empirical correlation that fits the vaporizing spray spreading angle data for the 246 μm orifice was suggested by Siebers[10].

$$\tan(\theta/2) = c\cdot\left[\left(\frac{\rho_a}{\rho_f}\right)^{0.19}-0.0043\left(\frac{\rho_f}{\rho_a}\right)^{0.5}\right] \quad (9)$$

where the constant c is 0.260. The constant c in the above correlation is 0.276 and 0.255 for the 180 μm and 100 μm orifices in the other work[17].

Kim et al.[18] had introduced the above equation for the comparison of their measurement data of liquid-phase penetration and found to be in good agreement for only small bore injector at different ambient temperatures and injection pressures. Even though predicted maximum liquid-phase penetration was shown to be not in reasonable agreement with measured one for medium bore injector at two different ambient temperatures and injection pressures, there was no precise explanation about the reason in the literature. In their prediction, they assumed the area contraction coefficient as 0.8 and used the above empirical correlation that fits the vaporizing spray spreading angle for 246 μm orifice.

The maximum liquid-phase penetration, defined by Desantes et al.[7] as the axial spray penetration where the mass concentration required to evaporate the spray is acquired, can be calculated as

$$L = \frac{k_p^2 d_0 C_a^{0.5}}{C_{mv}\tan(\theta/2)}\left(\frac{\rho_f}{\rho_a}\right)^{0.5} \quad (10)$$

The above correlation was derived from the correlation for spray penetration suggested by Desantes et al.[12]. k_p is the penetration constant and was found to be 1.32 for all the nozzles and injection pressures employed by them. C_{mv} is the fuel mass concentration required to evaporate the spray. This values ranges from 0.30 to 0.36 for the different intake pressures, intake temperatures and constant injection pressure of 70 MPa and nozzle outlet diameter of 165 μm at inert atmospheric conditions. C_a is the area contraction coefficient at the orifice outlet. This value ranges from 0.81 to 0.91 for the different injection pressure and nozzle outlet diameter, etc.

From an experimental study of real multi-hole diesel nozzles under current DI diesel engines operating conditions, an empirical correlation for maximum liquid- phase penetration in diesel sprays based on nozzle flow parameters was recently proposed by Payri et al.[19] as follows.

$$L = \text{cte}\ d_0 C_a^{0.5} \rho_a^{-0.5} T_a^{-1.73} \Delta p^{-0.07} \tag{11}$$

where cte is the constant (=51412), T_a is the temperature in the combustion chamber at top dead center and Δp is the pressure drop equal to P_{inj}-P_{back}. C_a is the area contraction coefficient which is defined as the effective area divided by the geometrical area and ρ_a is the ambient density.

Compared with the empirical correlation by Siebers[10], this correlation seems to be very promising because of less parameters and simple expression. The constant cte includes the term for fuel density and spray angle. However, it is required to test this empirical correlation against other experimental results in order to assess the validity of the correlation.

2.1.3. correlations for arbitrary fuel blends

By extending the thermodynamic scaling law that predicts maximum liquid-phase penetration for single-component fuel, the empirical correlation (they refer to engineering correlation) for predicting maximum liquid-phase penetration of arbitrary fuel blends was proposed by Higgins et al.[9] as follows.

$$L/d_0 = kA^{\alpha}B^{\beta} \tag{12}$$

where A is the ratio of the fuel density to the ambient gas density, and B is the specific energy ratio defined as follows, respectively.

$$A = \rho_f / \rho_a \tag{13}$$

$$B = \frac{\sum_i m_i h_{\mathrm{vap},i} + (T_{b,\max} - T_f)\sum_i m_i C_{p,\mathrm{liq},i}}{C_{p,air}(T_a - T_{b,\max})\sum_i m_i} \tag{14}$$

where m_i is mass fraction of species i, h_{vap} is the latent heat of vaporization, $T_{b,\max}$ is the maximum boiling point temperature among the i species, T_f is the initial fuel temperature, T_a is in-cylinder gas temperature $C_{p,\mathrm{liq}}$ and $C_{p,\mathrm{air}}$ are specific heat at constant pressures for liquid and air, respectively. The above correlation of maximum liquid-phase penetration with the values of the correlation constants k =10.5, α = 0.58, and β=0.59 can predict the maximum liquid-phase penetration data with a standard deviation of 12% for all tested fuels.

Canaan et al.[20]pointed out that when considering the multi-component fuel data only, the introduction of mid-boiling point temperature instead of using 90% boiling point temperature can give better prediction results.

This correlation was introduced by Myong et al.[11] to study the vaporization characteristics and maximum liquid-phase penetration for multi-component fuels. It should be noted that they had used the different values of the correlation constants k=9.46, α= 0.56 and β= 0.62 from the original values suggested by Higgins et al.[9]. They concluded that the correlation overestimates the maximum liquid-phase penetration for mixed-fuels due to consideration of 75% boiling point temperature and other fuel properties such as fuel viscosity and surface tension etc. which are not taken into account in the correlation.

On the other hand, the modified engineering correlation for the maximum liquid-phase penetration of the emulsified fuel had been reported. Musculus et al.[21] had introduced the engineering correlation for the maximum liquid-phase penetration developed by Higgins et al.[9] for the comparison of liquid-phase penetration data for water-fuel emulsion spray. They found that the maximum liquid-phase penetration was not represented well by the engineering correlation with the real diesel fuel emulsions. In an attempt to improve the correlation, the B term of engineering correlation was replaced with the form of the energy ratio contribution from the rigorous single-component liquid scaling law of Siebers[10] as follows.

$$L/d_0 = kA^{\alpha}\sqrt{(2B+1)^2 - 1} \tag{15}$$

The value of α= 0.56 instead of β= 0.58 was used and the value of k was necessarily adjusted to k= 3.3 due to the drastic change in the form of B term. It should be noted that the definition of B in the above modified engineering correlation is consistent with Higgins et al.[9]. They concluded that the modified engineering correlation captured the increase in maximum liquid-phase penetration due to water addition at different operating conditions better than the original engineering correlation.

2.1.4 statistical correlations

A simple statistical correlation to predict the dependence of maximum liquid-phase penetration on nozzle hole diameter, injection pressure and gas density was reported by Desantes et al.[8] as follows.

$$L = kd_0^{1.13} \tag{16}$$

$$L = kP_{inj}^{-0.06} \tag{17}$$

$$L = k\rho_a^{-0.52} \tag{18}$$

The above correlations were obtained in conditions corresponding to actual common rail direct injection diesel engine with nozzle diameters from 115 to 200 μm, injection pressures from 300 to 1300 bar and gas densities from 21 to 32 kg/m^3.

It is clear from Eq. (17) that there is no significant effect of injection pressure on maximum liquid-phase penetration. These correlations are not universal due to the lack of information about the value of coefficient *k*. In addition, it is required to lump into one common format with a model-dependent coefficient.

2.2 Multidimensional model

The numerical approaches to computing sprays have undergone remarkable progress over the last 30 years. Multidimensional model for the predication of maximum liquid-phase penetration can be classified as the three groups, i.e. Lagrangian and Eulerian model, Eulerian model, and coupled model.

2.2.1 Lagrangian and eulerian model

The typical numerical approach involve a Lagrangian approach to the liquid phase and an Eulerian approach to the gas phase. This widely used technique is ingrained in most of the multidimensional models for the prediction of liquid-phase penetration,

Aneja and Abraham[22] had used the multidimensional model to study the penetration of the liquid fuel in a constant volume chamber under normal diesel engine conditions. In their work, the computed liquid-phase penetration is taken to be the distance, along the axis, from the orifice to the drop that is furthest from the orifice. They found that the computed liquid-phase penetration is dependent on the numerical resolution that is employed and grid independent results are not obtained. This will be attributed to the dependence of the computed Sauter Mean Radius (SMR) of the drops on the resolution. In addition, they pointed out that the grid dependence of the computed SMR and liquid-phase penetration is shown to arise from limitations of the collisions and coalescence model.

A dense-particle Eulerian-Lagrangian stochastic methodology, able to resolve the dense spray formed at the nozzle exit was, recently, proposed by Tonini et al[23] for the prediction of liquid-phase and vapour-phase penetrations of evaporating diesel sprays.

To minimize grid dependency effects, the method of local grid refinement with cells having sizes comparable to that of the dispersed droplet parcels is used. The various spray sub-models are assessed against experimental data. The effect of liquid atomization, evaporation, aerodynamic drag, droplet secondary break-up and fuel physical properties is thoroughly tested. They concluded that the results show a good agreement for all the tested parameters, giving confidence on the predictive capability of the developed numerical model.

2.2.2. Eulerian model

To obtain grid-independent results, two-fluid model which solves Eulerian field equations for both the gas and the liquid phases was employed by Iyer et al[24]. It should be noted that the liquid-phase penetration is defined as the axial location along the centerline where the liquid mass fraction reaches 1% in their study. To reduce the complexity of the problem and equations required to be solved, they employed locally homogeneous flow (LHF) model in which the gas and the liquid phase velocities are assumed to be the same, and the turbulence in the liquid phase is assumed to follow the gas-phase turbulence. They concluded that there is reasonable agreement of the computed trends with measurements for the cases where the injection pressure and the ambient temperatures are varied. However, there were discrepancies in the trends for low ambient densities. They pointed out that this may result from drop vaporization time becoming important or from the assumption of the LHF model because the two phases have significantly different velocities.

Iyer et al[(25)] had modified the two-fluid model for diesel sprays with LHF assumption to assess droplet size effects on the steady liquid-phase penetration in vaporizing diesel sprays. Transport equations for the liquid surface area concentration and the D^2-law for single droplet vaporization are employed to include the size effects. They found that the effect of drop sizes does not appear to be important in determining the variation of the liquid-phase penetration with orifice diameter, injection pressure and ambient temperature.

Recently, a multidimensional model for atomization based on an Eulerian single-phase approach was proposed by Lebas et al.[(26)]. This model improves the treatment of the interaction between the liquid and the gas phases in the very dense spray region, close to the injector nozzle. This approach considers the liquid and the gas phases as a mixture of a single flow with variable density and switches to Lagrangian calculations when the spray is considered to be diluted enough based on a dilution criterion such as a critical value of the liquid volume fraction. However, this model failed to predict the well known experimental trends, such as the no-effect of increasing injection pressure on liquid-phase penetration.

2.2.3. Coupled model

To overcome the numerical problem such as grid dependency, some workers had proposed the coupled model of computing spray atomization and vaporization processes not using a fully multidimensional CFD model but using a simpler one dimensional model. The one dimensional model provides source terms (mass, momentum and energy exchange) as input to multidimensional model. With this coupled approach, grid-independent results can be obtained because the source terms coming from one dimensional model are not at all dependant on the multidimensional model mesh refinement.

The interactive cross-sectional averaged spray (ICAS) method of Wan and Peters[(6)], the virtual liquid source (VLS) model of Abraham and Magi[(27)] and the work of Versaevel et al.[(28)] can be classified into the coupled model in this study.

In ICAS method, gas phase is modeled by 3D model (KIVA-II) and the liquid phase by 1D model (called CAS). An average droplet diameter as nearly 1/10 of nozzle diameter is assumed at the nozzle exit. Even though evaporation, droplet breakup, droplet heating and drag force are considered, atomization and coalescence are not taken into account. By comparing the calculated penetrations of the vapour-phase and the liquid-phase as well as the distribution of the fuel-air ratio with the results obtained with 3D model and the experimental data, grid-independent results can be obtained.

The Virtual Liquid Source (VLS) model for vaporizing diesel sprays was proposed by Abraham and Magi[(27)]. This model treats the liquid region of the spray as a source of mass, momentum and energy without directly computing the liquid phase. The assumption underlying the model is that the volume and mass occupied by the liquid component of the fuel is small relative to the volume and mass of the total injected fuel. The two model input parameters of maximum core length and the time to achieve the maximum core length are required in advance. They pointed out that this model does not have the limitations related to grid sensitivity of standard spray model in the multidimensional model discussed in the above section.

In the work of Versaevel et al.[(28)], 1D model based on the work of Naber and Siebers[(29)] for the prediction of vapour-phase penetration and on the work of Siebers[(10)] for the prediction of liquid-phase penetration was proposed. This coupled approach can be used in an engine simulation as long as the liquid phase does not impinge and as long as the gas density or the temperature in the chamber is not too low. Even though time and grid independent results can be obtained, they found that there was a slight disagreement between simulations and experimental data for the higher injection pressure (150 MPa). In addition, they recommended that 1D model should be checked with detailed experimental data on the effects of rate shaping on spray penetration.

2.3. Other model

The holistic hydraulic and spray model developed by Schmalzing et al.[30] can be classified into the other model in this work. In this model, 1-D in-house code called ISIS (Interactive Simulation of Interdisciplinary Systems) initially calculates the necessary time step size, the mass rate of injected fuel and the velocity of the fuel at the nozzle exist based on the geometric details of the injection system and the fuel properties. In the subsequent spray model, the number of required fuel parcels is determined from the spray angle, the time step and the initial fuel velocity. The droplet size and the number of droplet in the parcels are computed. The droplet mass based on the representative SMD and appropriate droplet velocity are also determined. Finally, the penetrations of the individual fuel parcels are computed by balancing the momentum of liquid, vapor and gas phases within the spray angle. The heating and evaporation laws are incorporated.

They concluded that the very good agreement between computed and measured liquid- and vapour-phase penetrations as well as maximum liquid-phase penetration could be obtained by this model. However, this model shows a tendency to predict slightly higher maximum liquid-phase penetration at very low temperatures than are measured. It is, therefore, required to improve the sub-model for droplet evaporation.

3. Discussions

According to the review of existing correlations and models, the maximum liquid-phase penetration is a function of fuel properties, in-cylinder conditions, and injection characteristics. The fuel temperature and fuel volatility will be the fuel properties to affect the liquid-phase penetration. The in-cylinder conditions include the ambient gas temperature and density. The nozzle hole diameter, injection pressure and aspect ratio can be belonged to the injection characteristics.

It is clear that the injection pressure had an insignificant effect on the liquid-phase penetration. Increasing the injection pressure causes an increase of the mass flow rate and of the injection velocity. These effects tend towards lengthening the liquid phase. However, they also cause a faster atomization and a faster mixing, because of the increase on air entrainment and the reduced average size of the drops. These opposite effects cancel each other out and hence maximum liquid-phase penetration is nearly unchanged.

The maximum liquid-phase penetration decreased with increasing ambient density and temperature. The maximum liquid-phase penetration, however, increases linearly with the increase of nozzle hole diameter.

It is required to analyze the relation between vapour-phase and liquid-phase penetrations for empirical models in vaporizing diesel spray conditions.

4. Conclusions

The existing models developed for the prediction of maximum liquid-phase penetration can be categorized as the zero-dimensional (empirical) model, the multi-dimensional model and the other model. The existing zero-dimensional model can be classified into four groups, i.e. correlations based on liquid jet break-up time, correlations for single-component fuels and the correlation for arbitrary fuel blends and statistical correlations. The existing multidimensional models for the prediction of maximum liquid-phase penetration can be classified into three groups, i.e. Lagrangian and Eulerian model, Eulerian model, coupled model. The other model includes holistic hydraulic and spray model. The maximum liquid-phase penetration is mainly affected by nozzle diameter, fuel volatility, injection pressure, ambient gas pressure, ambient gas density and fuel temperature.

In the case of empirical correlations incorporated with spray angle, the predicted results will be different according to the selection of correlation for the prediction of spray angle. The research for the effect of boiling point temperatures such as 90%, 75% and 50% on maximum liquid-phase penetration is also required.

In the case of multidimensional model, there exist problems of the grid and spray sub-models dependency effects. To obtain grid-independent results, the models such as Eulerian model, couples model and the holistic hydraulic and spray model are developed and proposed. Despite all the above details and efforts to improve the accuracy of diesel spray calculations, prediction of maximum liquid-phase penetration under highly evaporating conditions still remains as a problem.

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